

Status and Implications of BSM Searches at the LHC

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Abstract

The LHC has collided protons on protons at center-of-mass energies of 7 and 8 TeV between 2010-2012, referred to as the Run I period. We review the current status of searches for new physics beyond the Standard Model at the end of Run I by the ATLAS and CMS experiments, limited to the 8 TeV search results published or submitted for publication as of the end of February 2014. We discuss some of the implications of these searches on the existence of TeV scale new physics, with a special focus on two open questions: the hierarchy problem, and the nature of dark matter. Finally, we give an outlook for the future.

1 INTRODUCTION

The LHC is a proton-proton collider, designed to operate at a center-of-mass energy of $\sqrt{s} = 14$ TeV and to collect on the order of 100-300 fb⁻¹ of data [1]. At the end of 2012, the two multi-purpose LHC experiments (ATLAS [2] and CMS [3]) concluded what has come to be known as “Run I” in which the LHC operated at $\sqrt{s} = 7$ and 8 TeV, collecting integrated luminosities of approximately 5 fb⁻¹ and 20 fb⁻¹, respectively, at the two energies. Even at these reduced energies, the LHC has well explored the TeV scale.

The physics program of ATLAS and CMS rests on two pillars:

- Elucidating the mechanism of electroweak symmetry breaking (EWSB)
- Searching for physics Beyond the Standard Model (BSM)

With the discovery [4,5] in July 2012 of what appears to be the Standard Model (SM) Higgs Boson, the first part of the program has passed an important milestone. While much effort will still be devoted to the important task of precisely measuring the properties of this SM-like Higgs boson, there is now renewed attention to the second major goal of the LHC. The search for BSM physics has already been an active and robust activity at the LHC. It is only expected to intensify at Run II when the machine is upgraded to its design energy.

To a large extent, searches for new physics have been motivated by two long-standing puzzles:

I. The Hierarchy Problem: It was recognized long ago that the SM Higgs – along with any other elementary scalar particles – suffers from what has come to be known variously as the “naturalness”, “hierarchy” or “fine-tuning” problem [6–10]. Today it is most common to describe the problem in terms of the radiative corrections to the Higgs mass which depend quadratically on the high-energy cutoff Λ up to which the SM is valid. For instance, one has

$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2} \Lambda^2, \quad (1)$$

at one-loop in the SM from the coupling ($y_t \approx 1$) to the top quark. Requiring that this be of the same order as the Higgs mass itself, one arrives to the conclusion that the cutoff scale, and therefore the appearance of new physics, should be in the 1 TeV range. Conversely, if the SM is valid all the way up to the Planck scale ($\Lambda \approx 10^{19}$ GeV) the observed value of the Higgs mass could only be explained by fine-tuning the radiative corrections against the bare mass at the level of one part in 10³².

II. Dark Matter: Another major motivation for new physics at the TeV scale comes from dark matter (DM). The existence of DM is well established from numerous sources, astrophysical and cosmological, and for recent reviews see e.g. [11,12]. DM is the dominant component of matter in the universe, yet it interacts only very weakly with ordinary matter.

TeV-scale DM is motivated by the “WIMP miracle” paradigm, which is the observation that a stable TeV-scale particle with weak interactions has the right annihilation cross section in the early universe in order to account for all of the DM today.

In this article, we review the status of searches for new physics at the end of Run I at the LHC and discuss some of the implications. As is well-known by now, no BSM physics has been found so far, and there is a sense in the community that the LHC results are in tension with naturalness (see Eqn. 1). This lack of new physics, and the re-introduction of the fine-tuning problem that accompanies it, is commonly referred to as the “little hierarchy problem”. By surveying the LHC searches for new physics, together with their weaknesses, gaps and loopholes, we will examine the state of naturalness.

The remainder of this article is organized as follows. Sec. 2 provides an overview of theoretical ideas for BSM physics and reviews the most prominent models. This is followed in Sec. 3 with the current status of searches from the ATLAS and CMS experiments. In Sec. 4 we assess the implications for specific BSM models and review re-interpretations of LHC results in the literature. We attempt to enumerate the weaknesses in current searches and loopholes in their interpretation. Finally, in Sec 5 we conclude with a brief look towards the future of the LHC at close to its design energy of $\sqrt{s} = 14$ TeV.

2 THEORY OVERVIEW

2.1 Solutions to the Hierarchy Problem

As discussed in Sec. 1, a “natural” SM Higgs mass implies new physics at the TeV scale. However, this alone is not sufficient to completely solve the hierarchy problem. Generally, the new physics must also have some additional structure, such as new symmetries or strong dynamics, that shields the Higgs mass against quadratic divergences from even higher scales. In this work, we focus on two well-studied frameworks for solving the hierarchy problem – supersymmetry (SUSY) and composite Higgs.

2.1.1 Supersymmetry

Supersymmetry (SUSY) is the prime example of a solution to the hierarchy problem based purely on symmetries. (Composite Higgs models, to be reviewed in section 2.1.2, use a combination of symmetry and strong dynamics.) The basic idea of SUSY is that it groups bosons and fermions into “supermultiplets,” such that particles in the same supermultiplet have the same properties apart from their spin. In this way, the spin 0 Higgs boson is related to a spin 1/2 Higgsino. Since the Higgsino mass is protected by chiral symmetry in the

same way as the SM fermions, the Higgs mass becomes protected as well. In practice, what happens is that the quadratically divergent loop corrections to the Higgs mass in the SM are canceled by corresponding loops of superpartners. For instance, the one-loop top diagram that leads to Eqn. (1) is canceled by a one-loop top squark diagram.

In the Minimal Supersymmetric Standard Model (MSSM), the particle content of the SM is approximately doubled.¹ For every SM fermion, there is a spin 0 counterpart, e.g. for a quark q there is a squark \tilde{q} and for a lepton ℓ there is a slepton $\tilde{\ell}$. For every SM gauge boson, there is a spin 1/2 counterpart, gluons to gluinos \tilde{g} , W , Z and γ to wino, zino and photino, respectively. Finally, for the SM Higgs, the MSSM enlarges it to two Higgs doublets H_u and H_d , and they each have spin 1/2 superpartners called Higgsinos. Under EWSB the Higgsinos mix with the wino, zino and photinos; these become charginos $\tilde{\chi}^\pm$ and neutralinos $\tilde{\chi}^0$. Some cross sections for SUSY particle production are shown as a function of mass in Fig. 1 for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ -14 TeV.

One general problem for the MSSM and SUSY is the proliferation of parameters. The MSSM certainly includes the usual Yukawa couplings $\mathbf{Y}_{\mathbf{u},\mathbf{d},\ell}$ of the SM:

$$W_{Yukawa} = H_u Q \mathbf{Y}_{\mathbf{u}} U + H_d Q \mathbf{Y}_{\mathbf{d}} D + H_d L \mathbf{Y}_{\ell} E. \quad (2)$$

Here Q , U , D , L and E denote “superfields” containing the SM fermions and their superpartners. However, even in the supersymmetric limit, there are many more possible renormalizable interaction terms:

$$W_{RPV} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \mu'_i L_i H_u. \quad (3)$$

Here i, j, k are flavor indices that run over the three generations of the SM. These new interactions all involve at least one superpartner, so they are not present in the SM. They generically violate baryon and lepton number, as well as the approximate flavor and CP symmetries of the SM. Thus there are stringent constraints on these couplings, see e.g. [16] for an overview. These dangerous interactions can all be forbidden by imposing an additional discrete \mathbb{Z}_2 symmetry on the MSSM called R-parity, which assigns charge 1 to all superpartners and charge 0 to all ordinary SM particles.

One crucial byproduct of R-parity is that the lightest superpartner (LSP) is absolutely stable. Cosmological bounds strongly suggest that the LSP must be neutral, in which case it could be a WIMP DM candidate. At the LHC, pair-produced superpartners² cascade decay down to the LSP, producing jets and leptons along the way. The LSP escapes the detector like a heavy neutrino, implying a missing transverse energy (E_T^{miss}) signature. Therefore, searches for jets and/or leptons and E_T^{miss} are among the best ways to search for SUSY at the LHC.

¹For an excellent review of the MSSM and SUSY phenomenology, see [13].

²Single production is forbidden by R-parity.

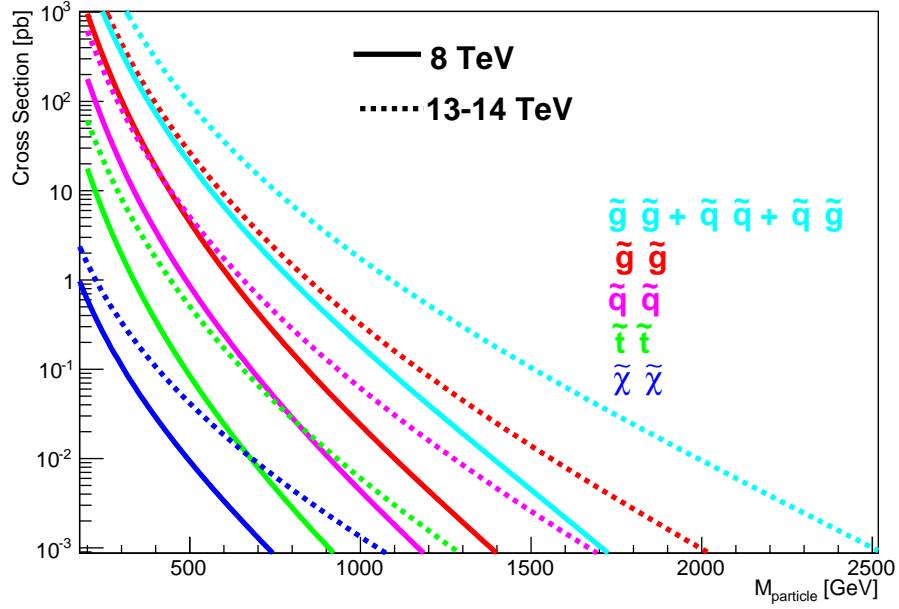


Figure 1: Cross sections for SUSY particle production. at $\sqrt{s} = 8$ TeV and 13-14 TeV. The colored particle cross sections are from NLL-FAST [14] and evaluated at $\sqrt{s} = 8$ TeV and 13 TeV; the electroweak pure higgsino cross sections are from PROSPINO [15] and evaluated at $\sqrt{s} = 8$ TeV and 14 TeV. The electroweak pair production cross section is sensitive to mixing, and the higgsino cross sections (shown in the figure) are approximately a factor of 2 lower than the pure wino case.

Of course, it is possible to reduce or even eliminate the E_T^{miss} signature by compressing the LSP mass against other particles, or elongating the decay chain, or turning on a small amount of R-parity violation (RPV). As the E_T^{miss} -based searches set stringent limits, there is increasing interest in such scenarios.

In addition to the RPV supersymmetric operators, there are also many dangerous R-parity-conserving interactions when SUSY breaking is taken into account. If SUSY were unbroken, the superpartners would be degenerate with their SM counterparts. Since the superpartners have not yet been observed, SUSY must be realized as a spontaneously broken symmetry in Nature. The superpartner spectrum is parametrized by the soft SUSY-breaking Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & \sum_{\tilde{f}=\tilde{q},\tilde{u},\tilde{d},\tilde{l},\tilde{e}} \tilde{f}^\dagger \mathbf{m}_{\tilde{f}}^2 \tilde{f} + \left(\sum_{r=1}^3 M_r \lambda_r \lambda_r + c.c. \right) \\ & + (m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + B\mu H_u H_d + c.c.) \\ & + (H_u \tilde{q} A_u \tilde{u} + H_d \tilde{q} A_d \tilde{d} + H_d \tilde{\ell} A_\ell \tilde{e} + c.c.). \end{aligned} \quad (4)$$

The terms on the first line describe the squark, slepton and gaugino soft masses; the terms on the second line describe the Higgs soft masses, and the terms on the third line describe the trilinear soft terms (the “A-terms”). While the soft masses do preserve baryon and lepton number, they generically violate the approximate flavor and CP symmetries of the SM. And unlike the RPV couplings, there is no symmetry that can forbid such terms. This is known as the SUSY flavor and CP problem.

Gauge Mediated SUSY Breaking (GMSB) is the most promising solution of the SUSY flavor problem.³ It postulates that SUSY breaking is only communicated to the MSSM via the SM gauge interactions. Since these are flavor blind, the resulting soft masses will be flavor blind. Minimal GMSB models were first constructed in the seminal works of [18–20]. The most general parameterization of GMSB was formulated in [21,22]. One distinctive feature of GMSB is that the gravitino is the LSP and is typically quite light, $m_{\text{gravitino}} \lesssim \text{keV}$. The lightest MSSM superpartner (which in GMSB can be any sparticle) becomes the next-to-lightest superpartner (NLSP) and it decays to its SM counterpart and the gravitino, e.g. $\tilde{B} \rightarrow \gamma + \tilde{G}$. So there are spectacular signatures such as $\gamma\gamma + E_T^{\text{miss}}$, $\gamma + \ell + E_T^{\text{miss}}$, and multileptons + E_T^{miss} . The NLSP lifetime is also a free parameter in principle, and the lifetime can range from prompt, to displaced, to detector-stable. In the latter case there are many powerful and inclusive searches for CHAMPS and R-hadrons, while for displaced signatures currently there are very few so far (see Sec. 4.3.4).

The complexity of SUSY parameter space is problematic for both theorists and for experimentalists who must design searches and set limits on specific slices of this parameter

³For a review of GMSB and original references, see [17].

space. As it is impossible to cover the entire parameter space by simulation, several complementary approaches are taken when estimating the sensitivity of the searches to SUSY signals. In the first approach, complete SUSY models are simulated; these models typically impose boundary conditions at a high energy scale, reducing the number of parameters to about five, and making it realistic to scan the parameter space by brute force. Examples are MSUGRA/CMSSM [23–28], and minimal GMSB and anomaly-mediated SUSY (AMSB) [29, 30] models.

The second approach is referred to as “simplified models” [31–34], and is commonly used in BSM searches in general. As applied to SUSY, the decay cascades are simplified by setting the masses of most SUSY particles to multi-TeV values, putting them out of range of the LHC. The decay cascades of the remaining particles to the LSP, typically with zero or one intermediate step, are characterized only by the masses of the participating particles, allowing studies of the search sensitivity to the SUSY masses and decay kinematics. A typical limitation of this approach is the fact that all events decay through only one chain; even within one decay chain, once the number of states exceeds two, various assumptions are typically imposed on the relationship between the masses, both to save computing time and to simplify the visualization of the final results.

One popular example of a simplified-model-type scenario are “natural” or “effective” SUSY models.⁴ It was noticed long ago that not all superpartners are equally important for the fine-tuning problem of the electroweak (EW) scale. For instance, in the MSSM, at tree-level only Higgsinos contribute to fine-tuning, at one-loop stops are most important, and at two-loops gluinos are most important. The idea of “natural SUSY” is to imagine that all but Higgsino, stop and gluino are decoupled from the LHC (in practice, heavier than ~ 10 TeV). This would be the minimal superpartner spectrum necessary to postpone the hierarchy problem to much higher scales. Aside from having a much simpler parameter space, the main benefit of “natural SUSY” is significantly weakened LHC constraints, primarily because decoupling the first generation squarks greatly decreases the SUSY production cross section.

2.1.2 Composite Higgs

Composite Higgs models attempt to solve the hierarchy problem through a combination of strong dynamics and symmetry.⁵ First, by positing that the Higgs is a composite bound state of an additional strongly-coupled sector (and not an elementary scalar), these models cut off the quadratic divergence of the Higgs mass at the compositeness scale. Direct searches, precision EW tests, and flavor tests all constrain the compositeness scale to at least the

⁴For recent reviews on “natural SUSY” models and original references, see e.g. [35, 36].

⁵For a recent review of composite Higgs models and many original references, see [37].

multi-TeV range. Therefore, modern composite Higgs models (especially after the Higgs discovery) generally also equip the composite sector with an approximate global symmetry G , in order to explain why the Higgs is a narrow, light state apparently well-separated from the other resonances of the composite sector. When G is spontaneously broken to a subgroup H at some scale $f \sim 1$ TeV, the SM Higgs emerges as a pseudo-Nambu-Goldstone boson (PNGB), much like the pion of QCD. In order to better satisfy precision EW constraints, it is generally assumed that H contains the custodial $SO(4)$ symmetry. G is also explicitly broken by the gauging of $SU(2) \times U(1)$ and by the SM Yukawa couplings. These radiatively generate a potential for the Higgs.

One popular and well-studied example is the “Minimal Composite Higgs Model” (MCHM) [38]. Here the strong sector has a global $G = SO(5)$ symmetry that is spontaneously broken down to $H = SO(4)$. After gauging a $SU(2) \times U(1)$ subgroup of $SO(5)$, there is one light PNGB with the correct quantum numbers to be a SM-like Higgs.

As in QCD, composite Higgs models predict a tower of resonances starting somewhere around the compositeness scale. Since the composite sector transforms under $SU(2) \times U(1)$, some of these resonances will carry EW quantum numbers.⁶ The lowest EW spin 1 resonance is usually called the ρ by analogy with QCD. The strongest limits on the m_ρ are 2-3 TeV from EW precision constraints (for a pedagogical overview of this, see [39]). This would put them out of reach of the LHC. Nevertheless, searches for them are ongoing (generally phrased as searches for W' particles). These resonances mix with the W and Z bosons so they can be produced from Drell-Yan and Vector Boson Fusion (VBF). They can decay in many ways, including WW , WZ , Wh , Zh , $t\bar{t}$ and $t\bar{b}$.

In addition to EW vector resonances, there are also generally colored fermionic resonances in composite Higgs models. These are necessary to realize the “partial compositeness” scenario that alleviates the flavor problem of composite Higgs models. Here the SM fermions q are assumed to mix with fermionic resonances \mathcal{O}_q from the composite sector:

$$\mathcal{L} \supset \lambda_q q \mathcal{O}_q + \dots \quad (5)$$

The 3rd generation is assumed to couple most strongly to the fermionic resonances; thus, the lightest one of these are usually referred to as “top partners”.

For the phenomenology of composite Higgs top partners, we refer to [40,41]. The former paper focuses on top partners in the MCHM, while the latter paper takes a more model-independent point of view. Starting from complete multiplets of the global symmetry G of the composite sector, and decomposing them into EW representations, a number of distinct top partners can emerge. This includes particles (often denoted by T and B) with the same

⁶One can also consider the phenomenology of spin 1 colored resonances. These are not required in composite Higgs models, but generically arise as KK gluons in extra dimensional models.

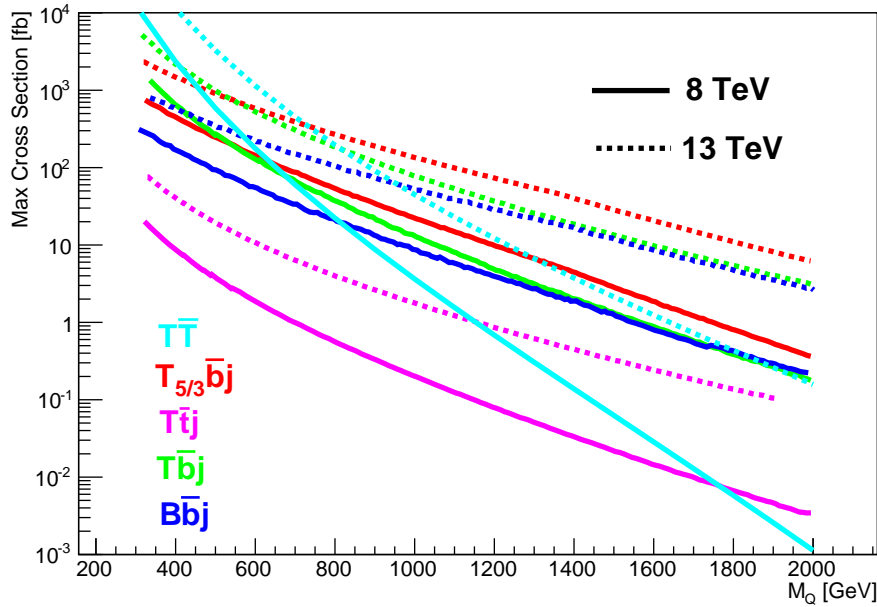


Figure 2: Cross sections for single [41] and pair [42] top partner production at $\sqrt{s} = 8$ TeV and 13 TeV.

quantum numbers as the top and bottom quarks, as well as particles with exotic electric charges such as $5/3$ (often denoted as $T_{5/3}$). These can be pair produced via QCD; then their cross sections depend solely on their mass and are essentially that of a heavy vector-like quark. One can also have single production via Wb , Wt , Zb and Zt fusion from a gluon-quark initial state, since these top partners mix with the third generation. This is more model dependent, since it depends on the unknown mixing parameter; more details are given in [40, 41]. Some typical cross sections for top partners produced singly and in pairs are shown in Fig. 2. The top partners primarily decay into Zt , Zb , Wt , Wb . Decays involving Higgses are also possible. So events have many b 's, leptons, jets and E_T^{miss} .

There is an important correspondence [43–47] between 4D composite Higgs models and extra-dimensional models such as the Randall-Sundrum model [48]. The holographic principle, most notably the AdS/CFT duality [49–51], is believed to relate weakly-coupled gravitational theories with strongly-coupled field theories living on their boundaries. This has given rise to the hope that composite Higgs models could be rendered calculable through holography. In the simplest 5D constructions, there is an “IR brane” where the SM fields are localized, and there is a “UV brane” where the composite sector is localized. These branes are separated by a compact extra dimension; if the spacetime metric in the 5th dimension is exponentially warped as in RS, then the warping connects the Planck scale on the UV

brane with the TeV scale on the IR brane. Such “holographic” composite Higgs models can be weakly coupled in 5D and can describe many of the properties of a strongly-coupled field theory in a calculable way. For instance, the dimensional reduction of a 5D theory down to a 4D theory results in towers of heavier states, the so-called Kaluza-Klein (KK) states. These are in direct correspondence with the towers of resonances expected in a QCD-like theory in 4D.

In the original RS construction, the Higgs is also localized on the IR brane. Therefore it is naturally of the same size as the KK modes, which in practice must be at least ~ 10 TeV due to flavor and precision EW constraints. Such models therefore suffer from a severe little hierarchy problem. This motivated the inclusion of a global symmetry spontaneously broken down to custodial symmetry, in which the Higgs is a PNGB, both alleviating the EW precision constraints, and explaining why the Higgs is lighter than the KK modes [38, 52]. In the extra-dimensional context, the global symmetry on the IR brane is gauged, and the Higgs propagates in the bulk as the fifth component of the gauge field.

2.2 Dark Matter

As discussed in Sec. 1, the connection of dark matter to the TeV scale (and hence the LHC) proceeds through the so-called “WIMP miracle”. If DM is a cold thermal relic, then its present day annihilation cross section is $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. Meanwhile, if DM interacts with the SM through the weak interactions (including Higgs exchange), then $\sigma \sim \frac{g^4}{m_\chi^2}$. This reproduces the desired cross section for $m_\chi \sim 1$ TeV.

Despite the connection to the TeV scale, direct searches for DM at the LHC are inherently challenging. Since DM should be neutral and colorless, it will show up as missing energy at the LHC. Searches for direct production must rely on hard initial state radiation (ISR) for triggering (leading to, for example, monojet+ E_T^{miss} and monophoton+ E_T^{miss} signatures), which reduces the rate. Furthermore, if DM is a WIMP, then its cross section is EW and not strong, further degrading the mass reach.

One popular approach for expressing the results of dark matter searches in a model-independent way is via effective field theory (EFT), see e.g. [53–55]. By expressing the dark matter interactions with the SM (e.g. quarks) via effective operators such as $\frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$, LHC searches can place bounds directly on the mediator scale Λ , and they can map these bounds into the same parameter space as the direct-detection bounds, since they proceed through the same effective operators. However, it is important to keep in mind that the EFT approach is only valid for mediator scales $\Lambda \gg m_\chi$, in practice several TeV for $m_\chi \sim \mathcal{O}(100 \text{ GeV})$ [55–58]. For lighter mediators (e.g. the h and Z , relevant to actual standard WIMPs), resonant effects and the general break down of the EFT imply that the limits set using the EFT can be wildly off compared to those in a genuine UV completion.

3 SEARCHES FOR BSM PHYSICS

The ATLAS and CMS experiments have extensively searched for BSM physics using the 7 TeV and 8 TeV datasets in Run I. So far, these searches show no evidence for new physics and have set stringent limits on many BSM models. The searches are based on distinct experimental signatures, and while a particular search may report limits on a particular model, the search is typically sensitive to a wide range of models. Both ATLAS and CMS attempt to provide enough information in their publications so that interested readers can reinterpret (“recast”) the results in the context of some other model.

In this section, we briefly summarize the current status of such searches, focusing on those models most closely tied to naturalness: Supersymmetry and composite Higgs models (and the related searches for extra dimensions and black holes (BHs)). In addition, we present a brief summary on the searches for DM.

The review is limited to search results at 8 TeV which have been published or submitted for publication as of the end of February 2014. Both ATLAS and CMS have published an extensive array of search results based on 7 TeV data; most of these results have been superseded by preliminary results from 8 TeV which have been presented at conferences, but which are not reviewed in this article. The full list of results, both preliminary and published can be found at [59, 60].

3.1 Supersymmetry

3.1.1 Searches for gluinos and 1st/2nd generation squarks

For a fixed particle mass, gluinos and first-generation squarks $\tilde{q} = (\tilde{u}, \tilde{d})$ have the largest SUSY production cross sections at the LHC (see Fig. 1), proceeding through $pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$. They are thus prime candidates for the most inclusive searches for SUSY. Squarks of the first and second generation are often assumed to be mass degenerate in LHC searches (to better comply with flavor constraints).

In simplified models with very heavy squarks, gluinos decay via $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0$ or $q\bar{q}'\tilde{\chi}_i^\pm$. If gluinos are very heavy, squarks decay via $\tilde{q} \rightarrow q\tilde{\chi}_i^0$ or $q'\tilde{\chi}_1^\pm$. Ignoring additional jets from initial- or final-state radiation, event topologies with two, three and four jets are therefore expected for $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ production, respectively. More complicated decay cascades lead to larger numbers of jets in the final state. When electroweak partners are produced in the decay chain, leptons can be present via the decays $\tilde{\chi}_1^\pm \rightarrow W^{(*)\pm}\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \rightarrow Z^{(*)}\tilde{\chi}_1^0$. The most inclusive searches for SUSY are therefore based on the presence of multiple jets; zero, one or more leptons; and E_T^{miss} , where the latter arises (in part) from the two LSP’s in the event. Useful observables include E_T^{miss} and H_T , defined as the scalar sum of the transverse momenta

of the jets (and sometimes the leptons⁷) in the event. The sum $H_T + E_T^{\text{miss}}$, sometimes called the effective mass (m_{eff}), reflects the mass difference between the initially-produced SUSY particle and the LSP, and is approximately independent of the details of the intermediate states in the decay cascade.

The most sensitive search as of the end of February 2014 [61], covering the full 8 TeV dataset, uses selection criteria explicitly tuned for jet multiplicities from 3 up to 8 or more; 36 signal regions, binned in H_T , H_T^{miss} , and the number of jets, are considered. Squarks of the first and second generation below 780 GeV are excluded for LSP masses below 200 GeV in a simplified model of $pp \rightarrow \tilde{q}\tilde{q}$ where $\tilde{q} \rightarrow q\tilde{\chi}_i^0$. The limit reduces to approximately 450 GeV if only one squark flavor and chirality is accessible. Gluinos below 1.1 TeV are excluded for light LSP masses in a simplified model of $pp \rightarrow \tilde{g}\tilde{g}$ where $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$.

Limits on gluino pair production in simplified models with charginos in the decay cascade are obtained in an ATLAS high multiplicity jets+ E_T^{miss} search [62] with no leptons. In a model where $pp \rightarrow \tilde{g}\tilde{g}$ and $\tilde{g} \rightarrow qq'\tilde{\chi}_i^\pm \rightarrow qq'W^{(*)\pm}\tilde{\chi}_1^0$, gluinos below approximately 1 TeV are excluded for LSP masses below 200 GeV, assuming the chargino mass is halfway between the LSP and gluino masses. The CMS search [61] excludes gluinos below 1.2 TeV in a similar scenario, but also allows for the decay mode $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \rightarrow q\bar{q}Z\tilde{\chi}_1^0$ with equal probability. Searches based on jets plus E_T^{miss} and additional leptons reach roughly similar conclusions in such models. A CMS search [63] based on 34 signal regions with same-sign dileptons binned in H_T , E_T^{miss} , and the number of (b -tagged) jets excludes gluinos below about 900 GeV for light LSP's, approximately independent of assumptions about the chargino mass.

Table 1 summarizes the approximate mass reach for a massless $\tilde{\chi}_1^0$ for selected analyses that are representative of an abbreviated set of probed decay modes. The table also shows the maximum value of the $\tilde{\chi}_1^0$ mass above which no exclusion limits exist, as well as the minimum mass difference between the initially produced SUSY particle and the LSP (ΔM) below which no exclusion limits exist. This is discussed further in Section 4.3.1.

3.1.2 Searches for gluinos and 3rd generation squarks

Searches for gluinos and squarks of the third generation are particularly well-motivated by the “natural SUSY” scenario and have been carried out in many channels, utilizing various combinations of (b -tagged) jets, leptons, H_T and E_T^{miss} [62–67]. Even before the advent of the “natural SUSY” paradigm, it had been recognized that third generation squarks could be considerably lighter than those of the first- and second generation due to the possibility of significant left-right mixing and mass splitting, arising from the large Yukawa coupling.

In the scenario of gluino pair production followed by the three-body decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via an intermediate off-shell top squark, the best published limit as of the end of February

⁷Unless otherwise specified, the term leptons will refer to electrons and muons.

2014 [65] excludes gluinos up to a mass of 1260 GeV for LSP masses ranging up to almost 500 GeV. Additionally, the sensitivity is extended for smaller gluino-neutralino mass splittings in the region $m(\tilde{g}) - m(\tilde{\chi}_1^0) < 2m(t)$ and $m(\tilde{g}) - m(\tilde{\chi}_1^0) > m(W) + m(t)$, where the decay becomes four body and proceeds through an off-shell top quark.

For gluino decays via on-shell top squarks (followed by $\tilde{t} \rightarrow t\tilde{\chi}_1^0$), exclusion limits are presented fixing the gluino mass to 1000 GeV and varying the LSP and top squark masses or fixing the LSP mass to a value around 50 GeV and varying the top squark and gluino masses [65]. In the former model, the 1000 GeV gluino is excluded for all kinematically accessible top squark and LSP masses, provided the LSP mass is below approximately 520 GeV. In the latter model, the gluino mass limit degrades for smaller top squark masses, but still exceeds 1000 GeV for a top squark mass as low as 200 GeV. For the three-body gluino decay $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ via an intermediate virtual bottom squark, gluinos are excluded up to a mass of 1170 GeV roughly independent of LSP mass up to 500 GeV [66]. Other decay modes considered include $\tilde{g} \rightarrow b\bar{b}_1^* \rightarrow b\bar{t}\tilde{\chi}_1^+ \rightarrow b\bar{t}W^+\tilde{\chi}_1^0$ and the RPV decay $\tilde{g} \rightarrow tbs$ [63].

To cover the possibility where the gluinos are beyond reach, searches for direct production of third-generation squarks have also been made by both CMS and ATLAS. A CMS search [68] for $pp \rightarrow \tilde{t}\tilde{t}^*$, excludes top squarks with a mass below 630 GeV for a light LSP in a model where both top squarks decay via $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ to unpolarized top quarks, degrading to about 600 GeV for an LSP mass as high as 200 GeV. Similar limits are obtained in a model where both top squarks decay via $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ although the limits depend on the mass splitting between the chargino and the LSP, degrading as the chargino and the LSP become mass degenerate. The same CMS search also tackles the three-body decay $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$ via a virtual top quark, which can be significant if the mass difference between the top squark and LSP is sufficiently compressed. An interesting case is the top squark decay $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ where a small mass splitting between the chargino and the LSP renders the lepton-based searches ineffective; this topology is covered by an ATLAS search [69] for two energetic b -tagged jets plus E_T^{miss} vetoing events with leptons and additional jets. Top squarks with mass below 580 GeV are excluded for LSP masses up to approximately 200 GeV, assuming a mass splitting between the chargino and LSP of 5 GeV. For larger splittings, the limits weaken due to the increasing likelihood of successful reconstruction of a lepton from the chargino decay.

Allowing for additional jets in the event, ATLAS searches for the process $pp \rightarrow \tilde{b}\tilde{b}^*$ with $\tilde{b} \rightarrow b\tilde{\chi}_1^0$. The study of a topology where the two b -tagged jets recoil against a high- p_T jet (typically from initial-state radiation) gives the analysis sensitivity to compressed scenarios where the mass difference between the bottom squark and the LSP is relatively small. Bottom squarks with a mass below 620 GeV are excluded for small LSP masses, degrading only slightly up to an LSP mass of about 200 GeV.

A CMS search [70] considers a “natural SUSY” model with GMSB in which only the top squarks and higgsinos are accessible. The model considers top squark pair production followed by $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, or $\tilde{t} \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ^{(*)}\tilde{\chi}_1^0$, or $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ and where the $\tilde{\chi}_1^0$ decays to $h\tilde{G}$. One Higgs boson is required to decay in the diphoton channel while the other is accepted in either the diphoton or $b\bar{b}$ channels. Top squark masses below 360 to 410 GeV depending on the higgsino mass, are excluded.

3.1.3 Searches for charginos and neutralinos

Direct pair production of gauginos at the LHC is dominated by $\tilde{\chi}_1^+\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production in most of the MSSM parameter space. One search at 8 TeV has been published as of the end of February 2014, searching for associated chargino-neutralino production in the trilepton plus E_T^{miss} channel [71]. Assuming equal mass $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$, these gauginos are excluded below 345 GeV in models where $\tilde{\chi}_1^+ \rightarrow W^{(*)+}\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow Z^{(*)}\tilde{\chi}_1^0$ with a very light LSP, as shown in Table 1; the limits are approximately unchanged up to a LSP mass of about 75 GeV. The discovery of a relatively light Higgs boson also opens the possibility of the decay $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ and the inclusion of tau leptons in the analysis adds sensitivity via the $h \rightarrow \tau\tau$ channel. In models where $\tilde{\chi}_2^0$ decays exclusively via $h\tilde{\chi}_1^0$ and the Higgs boson decays according to SM branching ratios, degenerate $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ below approximately 140-148 GeV are excluded, for LSP masses below about 20 GeV. Results are also interpreted in a phenomenological MSSM (pMSSM [72]) framework where the strongly interacting SUSY particles, the sleptons and the CP-odd Higgs boson are all assumed to be out of reach; $\tan\beta$ is set to 10, the gaugino mass parameters M_1 is set to 50 GeV and limits are explored as a function of M_2 and μ . A pMSSM scenario where the right-handed sleptons become kinematically accessible is also considered.

3.1.4 Searches for long-lived particles

Searches for long-lived particles are theoretically well motivated. The possibility of a metastable bound state containing a gluino or a squark, the so-called R-hadron, was raised already in the earliest papers on MSSM phenomenology [73]. More generally, there is a large class of models within SUSY that predict the existence of long-lived particles, such as: GMSB, AMSB, RPV, and split SUSY [74, 75]. There are many reasons that such particles can have highly suppressed decay rates – their decays could proceed through very high dimension operators (GMSB and split SUSY), extremely small couplings (RPV), or extreme kinematic suppression (AMSB).⁸

⁸For recent reviews of metastable massive particles, see Ref. [76, 77].

In order to search for massive particles with long lifetimes, the analyses deal with “unconventional” signatures ranging from displaced vertices, disappearing tracks, slowly moving particles with a long time-of-flight, or heavy particles with such long lifetimes that they decay in the calorimeter out-of-time with the LHC bunch crossing.

The experimental signature for R-hadrons is complicated by the fact that they could have a significant probability of undergoing hadronic reactions in the detector material [78–80]. Several searches are therefore designed, utilizing different portions of the ATLAS and CMS detectors. A CMS search [81] based on the full datasets from both 7- and 8 TeV excludes gluinos with mass below 1233 to 1322 GeV, depending on the interaction model and the fraction of gluinos that form glueballs and therefore remain neutral and weakly interacting throughout the transit of the detector. Top squark R-hadrons are excluded below a mass of 818 GeV. Scalar taus are excluded below 500 GeV when directly and indirectly produced in a minimal GMSB model; directly produced staus are excluded below 339 GeV. Limits are also placed on Drell-Yan production of leptons with non-standard charge. An ATLAS search [82], also covering the full 7- and 8 TeV datasets, looks for R-hadrons that have stopped in the calorimeter material and decay during periods in the LHC bunch structure without pp collisions. The complementarity with respect to the searches described above is model dependent. Limits on the gluino, top squark and bottom squark masses of 832, 379 and 344 GeV, respectively, are obtained for an LSP mass of 100 GeV.

Although these searches cover a broad range of mechanisms for R-hadron interactions, there remains the possibility that a R-hadron remains neutral through the entire detector. This case would be covered by the search for a monojet plus E_T^{miss} signal, discussed in Sec. 3.3, although explicit limits have not been published. (See however [83, 84] for a recasting of monojet and SUSY searches for compressed gluino-bino and squark-bino simplified models, which would also be relevant to the all-neutral R-hadron scenario.)

Chargino production via $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 + \text{jet}$ or $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + \text{jet}$ in an AMSB-inspired scenario has been explored by ATLAS [85]. In these scenarios, the lightest chargino and the LSP are nearly degenerate such that the chargino decay proceeds via $\tilde{\chi}_1^+ \rightarrow \pi^+ \tilde{\chi}_1^0$ where the pion has a momentum of the order of 100 MeV. The search looks for events in which an isolated, high- p_T charged track “disappears” in the ATLAS tracking volume, the low-momentum pion going unobserved. An additional jet from initial-state radiation is required to trigger the event. In the minimal AMSB scenario, charginos with a mass below 270 GeV are excluded. More general limits are derived in the plane of the chargino mass versus the lifetime.

3.1.5 Searches for R-Parity Violating Supersymmetry

ATLAS and CMS have also performed searches for RPV SUSY. As mentioned in Sec. 2.1.1, these signatures show up with little-to-no E_T^{miss} in the event. As of the end of February

Table 1: Summary of the approximate mass reach for a number of simplified supersymmetry production/decay channels, for compressed and noncompressed decay topologies, from the LHC-8 TeV data using up to $\approx 20 \text{ fb}^{-1}$.

Mode	$\min(\Delta M)^a$ (GeV)	$\max \tilde{\chi}_1^0 \text{ mass}^b$ (GeV)	Mass limit (GeV) massless $\tilde{\chi}_1^0$	Reference
$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$	175	300	750	[64]
$\tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^0 qq\tilde{\chi}_1^0$	25	530	1160	[61]
$\tilde{g}\tilde{g} \rightarrow t\tilde{\chi}_1^0 t\tilde{\chi}_1^0$ $(m(\tilde{t}_1) \gg m(\tilde{g}))$	225	580	1260	[65]
$\tilde{g}\tilde{g} \rightarrow b\tilde{\chi}_1^0 b\tilde{\chi}_1^0$ $(m(\tilde{b}_1) \gg m(\tilde{g}))$	50	650	1170	[66]
$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 t\tilde{\chi}_1^0$	100	230 ^c	630	[68]
$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 b\tilde{\chi}_1^0$	15	260	620	[69]
$\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow W^{(*)} \tilde{\chi}_1^0 Z^{(*)} \tilde{\chi}_1^0$	25	120	345	[71]

^aThe minimum mass difference is shown, below which mass limits are not evaluated

^bMaximum value of $\tilde{\chi}_1^0$ mass for which a limit is quoted

^c165 GeV for off-shell top

2014, the experiments have published two such searches both using the full 8 TeV dataset. The first from CMS [86] selects events with at least three isolated leptons and b -jets, and targets signatures which arise from stop pair production with RPV decays. Several RPV couplings are explored, and excludes stop masses for two scenarios below 1020 GeV and 820 GeV for an LSP mass of 200 GeV. The second analysis also from CMS [87] searches for the pair production of three-jet hadronic resonances, and targets final states with only-light flavor jets and both light- and heavy-flavor jets. The results are interpreted in the context of pair produced gluinos decaying via RPV under two different scenarios, with and without heavy-flavor. For the light-flavor decay scenario, gluino masses are excluded below 650 GeV; for the heavy-flavor decay scenario, gluino masses are excluded between 200-835 GeV, for the first time.

3.2 Composite Higgs and Extra Dimensions

As discussed in Section 2, composite Higgs models predict the existence of light ($\lesssim 1$ TeV) colored, fermionic “top partners” which couple strongly to 3rd generation quarks, resulting in signatures with many b quarks, leptons, jets and E_T^{miss} . In addition, composite Higgs models predict the existence of EW spin 1 resonances which mix with the W and Z and thus have phenomenology similar to W' s and Z' s. These are generally constrained to lie above 2-3 TeV by precision EW tests. Finally, colored spin 1 resonances (the so-called KK gluons) are generically present in many concrete (holographic) models of composite Higgs, and these are much less constrained by precision EW. Searches for all of these resonances are ongoing at the LHC.

So far the experiments have performed targeted searches for: top partners with charge $5/3$ ($T_{5/3}$) decaying to a top quark and a W boson [88]; top partners with charge $2/3$ (T) decaying to either a b quark and a W , a top quark and a Z boson, or a top quark and a Higgs boson [89]; a W' decaying to $t\bar{b}$ [90]; excited tops decaying to a top quark and a gluon [91]; and generic searches for anomalous production of $t\bar{t}$ that constrain Z' s and KK gluons [92].

In each of these searches $t\bar{t}$ is a large background and they therefore exploit the kinematic differences between the particles and the top background. A variety of distinguishing kinematic variables are used in these analyses, and examples include: invariant mass reconstruction (such as M_{tb} in the $W' \rightarrow t\bar{b}$ search, or $M_{t\bar{t}}$ in the anomalous $t\bar{t}$ production search), H_T , and more sophisticated multivariate tools (such as a boosted decision tree in the T search).

No evidence for top partners or vector resonances has been found in the LHC data so far, and stringent limits have been placed on a variety of scenarios. The exclusion limits on heavy resonances such as W' , Z' and Randall-Sundrum Kaluza-Klein (RS KK) gluons are in the 2 TeV range, whereas limits on vector-like top partners are in the 600-800 range. In Table 2 we summarize the current status of the 8 TeV searches from the LHC experiments.

In models of extra dimensions, access to quantum gravity at the TeV scale can lead to large rates for black hole (BH) production at the LHC [93–95]. Searches at the LHC have been performed for both “small” quantum BHs and “large” semiclassical BHs. In the latter case, the experimental signature would present itself as a high multiplicity of high p_T particles, produced as the semiclassical BH evaporates via Hawking radiation. Meanwhile, “small” quantum BHs would only have enough energy to decay to small multiplicity of particles, yielding a signature which is distinct from the semiclassical case.

The ATLAS and CMS experiments have searched for both such signatures for BHs and the current status is summarized in Table 2. In the CMS search [96], 12 fb $^{-1}$ of the 8 TeV data is used and explores events with large particle multiplicities. Model-dependent limits are obtained for several scenarios (such as the ADD model and string balls) and assumptions

Table 2: Lower mass limits (or ranges of lower limits) on top partners and vector resonances from Composite Higgs models and limits on extra dimensions. These LHC searches use the 8 TeV data up to $\sim 20 \text{ fb}^{-1}$, unless otherwise noted. The limit is on the mass of the heavy particle searched for, unless otherwise indicated. The abbreviations are defined in the text.

Search	Signature	Limit	[Ref.]
$W' \rightarrow tb$ resonances	ℓ +jets	2.05 TeV	[90]
$T_{5/3} \rightarrow tW$	same-sign dileptons	800 GeV	[88]
$T_{2/3} \rightarrow bW, tZ, tH$	ℓ +jets and dileptons	687 - 782 GeV	[89]
$t^* \rightarrow tg$	ℓ +jets	803 GeV	[91]
Anomalous $t\bar{t}$ production	ℓ +jets and all-hadronic	Z' : 2.1 - 2.7 TeV RS KK gluon: 2.5 TeV	[92]
microscopic BH	large S_T , jets, ℓ s, γ s and E_T^{miss}	4.3-6.2 TeV	[96] (12 fb^{-1})
quantum BH	ℓ +jets	5.3 TeV	[97]
quantum BH	γ +jets	4.6 TeV	[98]
ADD BH	like-sign dimuons	5.1-5.7 TeV	[99]

(such as rotating or non-rotating BH, or the number of extra dimensions) and are all in the roughly multi-TeV range. In addition, model-independent limits are provided as a function of the scalar sum of the p_T s of all the final-state objects, and the particle multiplicity, which allows straight-forward possible re-interpretation of the results. ATLAS has performed three searches for extra dimensions: two searches target quantum BH in either the lepton+jets final state [97] or the photon+jet final state [98]; and the third search targets an ADD model with like-sign dimuons [99]. Again, the lower mass limits are reported for several different scenarios and model assumptions and are in the 5 TeV range, as summarized in Table 2.

3.3 Direct Searches for Dark Matter

In addition to the searches for SUSY described above which provide a possible candidate for dark matter (e.g. the LSP), the LHC experiments have searched for direct pair production of WIMP DM particles.⁹ Since the WIMPs escape the detector without interacting, in order to be able to trigger on them, they are also assumed to be produced in association with a particle X , where X can be a jet, photon, or a vector boson. This gives rise to a mono- $X+E_T^{\text{miss}}$ signature. Although searches for DM have been extensively explored with the 7 TeV data

⁹The pair production is a consequence of the assumed parity symmetry that keeps the WIMPs stable.

and in preliminary results from 8 TeV data, there is currently only one such published result as of the end of February 2014. The recent publication from ATLAS [100] uses the full 8 TeV dataset and searches for a single hadronic large-radius jet whose mass is consistent with that of a W or Z boson, and is recoiling against large missing transverse momentum. Limits on the DM-nucleon scattering cross section as a function of the mass of the DM particle are set in the context of EFT, as described in Section 2.2, and are reported for both spin independent (vector-like) and spin-dependent (axial-vector-like) scattering. The results are also presented alongside those from direct dark matter detection experiments, however, it is important to note that direct comparisons using the EFT approach has important caveats as was briefly reviewed earlier in Section 2.2.

4 IMPLICATIONS

4.1 Implications for Specific Models

Prior to the LHC turn-on, a number of benchmark “complete” SUSY models were studied both in the theoretical literature and by the LHC experiments. In this section we review the current status of some of these models in the aftermath of Run I.

Perhaps the most studied benchmark model has been the constrained MSSM (CMSSM). Here the vast MSSM parameter space is reduced to just five parameters set at the GUT scale: m_0 (common sfermion mass), $m_{1/2}$ (common gaugino mass), A_0 (common trilinear soft term), $\tan\beta$, and the sign of μ . Fits to existing data in the CMSSM framework hinted at a SUSY mass scale in the hundreds of GeV range, although this value was primarily driven by the deviation from SM expectations in the measurement of the anomalous magnetic moment of the muon (see e.g. the discussion in [101, 102]). At the end of Run I, the situation of the CMSSM is much different. For the most up-to-date fits and references to earlier work, see [103, 104]. The Higgs at 125 GeV (to a large extent) and the direct LHC searches (to a lesser extent) have pushed the superpartners up much higher in mass, with stops $\gtrsim 750 - 1000$ GeV and gluinos and squarks $\gtrsim 1500 - 2000$ GeV now being required.

Another popular “complete” model with a greatly reduced parameter space is Minimal Gauge Mediation (MGM) [18–20]. Here some number of $\mathbf{5} \oplus \bar{\mathbf{5}}$ messengers generate flavor-diagonal soft masses at a messenger scale M . The soft masses are proportional to a common scale Λ . Together with the gravitino mass $m_{3/2}$ and the usual Higgs parameters $\tan\beta$ and $\text{sign}(\mu)$, these form the parameter space of MGM. Here the Higgs mass constraint alone is enough to push the soft masses into the multi-TeV range and basically out of reach of even the 14 TeV LHC [105].

The common theme to both of these examples is that for simple, constrained models

based on the *MSSM*, requiring a 125 GeV Higgs mass is generally more powerful than any individual LHC search in constraining the parameter space. In the *MSSM*, the Higgs mass is bounded at tree-level to be less than m_Z . So $m_h = 125$ GeV requires [106–110] large radiative corrections: either stops $\gtrsim 1$ TeV with large A -terms (the “max-mixing scenario” [111–113]), or in the absence of A -terms, very heavy stops $\gtrsim 8 - 10$ TeV. In constrained models such as *CMSSM* and *MGM*, where all of the superpartner masses are controlled by just a few parameters, requiring such heavy stops generally also pushes the rest of the spectrum out of reach.

Of course, even models based on the *MSSM* need not be so constrained as the *CMSSM* and *MGM*. For example, since the Higgs discovery, much effort has been devoted to extending *GMSB* models in order to realize large A -terms [114–124]. Such models, while often still out of reach of 7-8 TeV LHC, could be accessible at 14 TeV. One can also consider going beyond the *MSSM*; adding additional interactions can circumvent the tree-level bound. For instance, the Higgs mass can be raised by couplings to additional singlets (as in the *NMSSM*¹⁰) or by adding additional gauge interactions [126].

4.2 Broader Implications

Given the vast multitude of LHC searches for new physics that have been performed by ATLAS and CMS in many different channels, each setting a limit on a specific model or simplified model, it can be challenging to draw more general lessons. Many theorists have endeavored to reinterpret or “recast” LHC analyses, in order to understand broader implications, or in order to understand the constraints on their favorite models and potential loopholes in existing searches.¹¹ In this short review, we cannot do justice to the many recasting works out there. Instead we will attempt to highlight some recent examples that make use of 8 TeV LHC results. In this section we concentrate on reinterpretations that reach broader conclusions, while Sec. 4.3 is devoted to a general discussion of loopholes.

Perhaps the largest single theme driving recasting research is “natural SUSY”. As discussed in Sec. 2, in the *MSSM*, the Higgsino, stop and gluino are most important for naturalness in SUSY. Much effort has been devoted to recasting LHC analyses for simplified models motivated by “natural SUSY”, beginning with the work of [128–132]. More recently, for gluinos, an extensive study [133], reinterpreting nearly all relevant Run I LHC searches concludes that a gluino with a mass below approximately 1 TeV is very likely excluded for a very broad range of scenarios (RPC, RPV, hidden valleys, top dilution, etc.), provided that the gluino produces either E_T^{miss} or top quarks in the decay chain. If the tops and E_T^{miss} can

¹⁰For a review of the *NMSSM* see e.g. [125].

¹¹For a comprehensive list of references to such papers (and an interesting proposal for a potentially efficient shortcut to recasting), see [127].

be diluted sufficiently such that the final state is all hadronic, then the limit on the gluino could be lowered to $m_{\tilde{g}} \gtrsim 800$ GeV.

In [134], a study of “natural SUSY” production recasted three 8 TeV LHC searches and found that $m_{\tilde{g}} \gtrsim 1.2$ TeV and $m_{\tilde{t}} \gtrsim 700$ TeV for $m_{\tilde{H}} \lesssim 300$ GeV for a few simplified models with tops and $E_{\text{T}}^{\text{miss}}$ in the final state. See also [135, 136] which obtained similar limits on stop production using ATLAS and CMS direct stop searches.

Other works have focused on the possibility that the LSP decays via RPV in “natural SUSY”. In the comprehensive work of [137, 138], stop production with RPV was exhaustively classified. All possible decays, either directly via RPV, or through an intermediate Higgsino LSP, were classified and an extensive list of 7 and 8 TeV LHC searches were recasted to derive the current constraints on all of these scenarios. While in many instances (e.g. those with LLE or LQD decays that give rise to leptons and $E_{\text{T}}^{\text{miss}}$), the limits on stops were near their kinematic limit ~ 700 GeV, many scenarios are also identified (for example $\tilde{t} \rightarrow b\tilde{H} \rightarrow b\tau qq$ via RPV) where there is *no current limit* on the stop mass from the LHC!

Meanwhile, for composite Higgs models, the focus of recasting has largely been on fermionic top partners X .¹² Existing LHC searches use the same-sign dileptons channel, motivated by decays such as $X \rightarrow tW$. A common theme seems to be that the LHC searches assume 100% BR’s into specific final states (such as tW or tZ), whereas realistic models will have more complicated, mixed BR’s. See e.g. [40, 140, 141] for recasts of 7 TeV same-sign dileptons searches.

For more recent recasting works that use the full 8 TeV dataset, see e.g. [142–145]. These works generalize existing LHC searches to other scenarios. For instance, [142] considers the constraints when both $T_{5/3}$ and B are light, and can be both singly and pair produced. It is shown that the reach of existing same-sign dileptons searches can be increased somewhat from 770 GeV to roughly 850 GeV in some corners of parameter space. In [143], a comprehensive survey of the current status of the Littlest Higgs with T-parity (LHT) model is given. By recasting a number of LHC SUSY searches and combining with other constraints, a limit of 640 GeV on the compositeness scale f is claimed. In [144] a comprehensive study of bottom-partners in composite Higgs models is given. Combining current LHC limits with precision constraints, a best fit point of $v^2/f^2 \sim 0.07$ is determined. Finally, in [145], the bounds on charge 8/3 top partners are studied, which could be present even in the MCHM if the top partner is embedded in a **14** of $SO(5)$. Recasting same-sign dilepton searches a limit of $M_{8/3} > 940$ GeV is obtained. The CMS BH search [96] is also considered, which is not yet competitive.

¹²However, see the recent work of [139], where some LHC searches were recast in terms of limits on composite Higgs vector resonances.

4.3 Weaknesses, Loopholes in Current Searches

Although the searches for new physics beyond the SM performed by the LHC experiments are broad and comprehensive, there are still some areas which remain less well explored. In addition, in some cases, especially in SUSY searches, there are important assumptions made in the interpretations of the results which are worth noting. Here we attempt to summarize these weaknesses or loopholes, both by the experiments and in the theoretical literature, and serve as a list of areas for improvement in future searches.

4.3.1 Compressed Spectra

In the context of R-parity conserving SUSY models, there is a weakness in the case of “compressed SUSY” where the mass difference between the initially produced SUSY particle and the LSP is small, leading to lower E_T^{miss} in the final state and lower signal acceptance. While compressed spectra may at first seem to require some additional tuning, examples exist in the literature where this is not the case [146, 147].

With a few exceptions, ATLAS and CMS do not generally attempt to set limits in the region of very small mass differences (ranging from 25 to 175 GeV, depending on the channel) because the signal acceptance depends strongly on the modeling of initial-state radiation. Table 1 shows that mass limits are noticeably weaker for compressed decay spectra. For example, a natural scenario of pair production top squarks with mass 500 GeV decaying via $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ to a LSP of mass 250 GeV is still not ruled out. The production of $\tilde{\chi}_1^+\tilde{\chi}_2^0$ in the “natural SUSY” scenario where the electroweak partners are mostly Higgsino-like and hence highly mass-degenerate, is also unconstrained by the LHC, even taking into account re-interpretations of LHC monojet searches [148–151]; current limits on Higgsino LSPs are essentially no better than LEP! Even with mild compression, searches for electroweak partners all fail if the LSP has a mass greater than about 100 GeV.

4.3.2 Model Assumptions

A second loophole in current BSM search limits arises from the assumptions on decay branching ratios, for example as in the SUSY simplified models. Typically the decay is assumed to proceed via a single channel with 100% branching ratio. As of the end of February 2014, the LHC experiments have not presented SUSY search limits as a function of branching ratio, except in the search for top squarks [68] where the mass limits are recalculated under the conservative (but pessimistic) assumption that either the search in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ channel or the search in the $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ dominates.

As shown in many studies by theorists, mass limits from individual searches that assume 100% branching ratios can degrade significantly when applied to “realistic” scenarios with

complicated branching ratios. For example, in [152], a study of “natural SUSY” spectra recasted four different 7 TeV LHC searches in exclusive channels (jets+ E_T^{miss} jets+lepton+ E_T^{miss} opposite-sign dileptons+ E_T^{miss} and same-sign dileptons+ E_T^{miss}). Here it is shown that for a sufficiently complicated spectrum, the limit from any one of these searches was degraded because of branching ratios, but full sensitivity could be recovered by combining channels. Similar studies for direct stop/sbottom production can be found in [136, 153], where the role of branching ratios $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ or $\tilde{t} \rightarrow b\tilde{\chi}_1^+$, as well as $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ or $\tilde{b} \rightarrow t\tilde{\chi}_1^-$, are explored. Finally, in [148, 154, 155] the effect of the branching ratios in chargino-neutralino production on current LHC limits is explored, specifically $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$ vs. $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$.

Another example which demonstrates the sensitivity of results on the assumptions of the model is the dependence of SUSY limits on flavor mixing. An illustration of this can be found in [156] which studies the impact of stop-scharm mixing on the top squark bounds, and find that they can be appreciably lower. In addition, it is also shown that large stop-charm mixing can result in interesting and unexplored signatures such as $t\bar{c}(c\bar{t}) + E_T^{\text{miss}}$, which could be searched for immediately.

A final example of the dependence on model assumptions we discuss here is in the SUSY cross section calculation. For second generation squarks $\tilde{q} = (\tilde{c}, \tilde{s})$, essentially only production via $\tilde{q}\tilde{q}^*$ is available, since the $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ processes are greatly suppressed by PDFs unless q corresponds to a valence quark. Therefore, their rates are generally reduced relative to those for the first generation squarks [157]. The squark production cross section would also be lowered if the gluino is a Dirac fermion [158, 159].¹³ Other interesting examples with lower production cross sections are the ideas of “folded SUSY” [160] and “twin SUSY” [161, 162] in which the partners of the colored SM particles do not carry QCD charges.

4.3.3 Scans for Gaps in the Coverage

Scans of the pMSSM have been used to search for possible gaps in the coverage of LHC searches for SUSY [163–168]. At the time of Ref. [163], corresponding to public results available in September 2012, the authors conclude that viable models exist containing first/second generation squarks, gluinos and third generations squarks with masses below 600, 700 and 400 GeV, respectively. The authors of these scans have identified mechanisms that allow low-mass pMSSM points to survive the LHC searches. They essentially confirm loopholes already described above: *i*) lowering the production cross section for first/second generation squarks by splitting the mass degeneracy, *ii*) compressed decay chains, and *iii*) branches to multiple final states in the decay cascade.

¹³A Dirac gluino also leads to lower fine-tuning.

4.3.4 Displaced Decays

As discussed above in section 3.1.4, searches for heavy, long-lived particles are well-motivated by a number of theoretical scenarios in SUSY and beyond. The LHC experiments have searched for such signatures primarily with the 7 TeV data and have only a few results with the 8 TeV data (see Sec. 3.1.4). These analyses are typically very inclusive and powerful and target a large class of models. However, these searches cover typical lifetimes \gtrsim a few nanoseconds (10 cm), whereas intermediate lifetimes of 0.01-1 ns (corresponding to moderately displaced decays in the tracker volume) are much less constrained. For example, see [169] and [170] for a discussion of the weaknesses and discovery prospects in the LHC searches for long-lived particles in the context of GMSB and RPV respectively. There are several challenges to successfully perform these analyses, which include designing triggers and specialized reconstruction algorithms specific to the search. Nevertheless, the LHC experiments would benefit from designing searches to target this uncovered and more challenging range of longer-lived particles.

4.3.5 Searches for Very Unusual Signatures

It is crucial that searches for very unusual signatures, in particular those which may be missed by other searches, be performed by the LHC experiments. In addition, a variety of unusual signatures are predicted by many different models which address naturalness; for example, see [171] for a recent review. Although, many of these “unexpected” new signatures have been searched for at 7 TeV, many of them have not yet been repeated by the LHC experiments with 8 TeV data. We highlight some examples here.

Hidden Valley models [172] provide solutions to the hierarchy problem, and postulate a new, low mass hidden sector that is only very weakly coupled to the SM. One way this hidden sector could reveal itself is through the production of many light particles in the final state and appear as a collimated stream of leptons, which are referred to as “lepton-jets”. (Such signatures were recently motivated by various astrophysical anomalies in the context of indirect DM detection [173,174].) Searches for lepton-jets have been performed at 7 TeV [175, 176] but have not yet been repeated or extended in 8 TeV. Dedicated reconstruction tools are required for such searches and increasing pile-up can pose an additional challenge.

Another class of hidden valley models predict new particles called “quirks” which transform under a new strong force called “infracolor” [177]. These “quirks” are quark-like and fractionally charged. These were searched for by CMS using the 7 TeV data using the signature of tracks with associated low rate of energy loss in the silicon tracker [178], but has yet to be repeated with the 8 TeV data by either experiment.

Despite the fact that such searches for very unusual signatures are potentially challenging

and require dedicated efforts, they should not be neglected and should continue to be searched for by the LHC experiments using the 8 TeV data and beyond.

5 OUTLOOK

5.1 Expectations for 14 TeV

The LHC is currently shut down (LS1) and data-taking is expected to resume at close to the design center-of-mass energy of 14 TeV in 2015. In the ensuing data-taking period, an integrated luminosity of approximately 100 fb^{-1} is expected to be collected by both ATLAS and CMS. This will be followed by another shutdown (LS2) during which the injector chain will be modified to approximately double the instantaneous luminosity, after which another 200 fb^{-1} is expected to be collected. Currently under discussion are plans to further increase the luminosity of the LHC by an additional factor of 2.5, leading to a total integrated luminosity of 3000 fb^{-1} by some time in the 2030's.

Several large-scale planning exercises for the future of high energy physics have been held in the last two years [179–181]. The increase in the energy to 14 TeV extends the kinematic reach to higher mass, while the increase in integrated luminosity extends the sensitivity for lower mass processes with small cross section and for difficult kinematic topologies; an example can be seen in Fig. 1. Both ATLAS and CMS have made projections of the expected physics performance for integrated luminosities of 300 and 3000 fb^{-1} . The ATLAS projections are mostly derived from fast simulations incorporating parametrizations of detector performance obtained from detailed detector simulations, and reoptimizing the analysis. The detailed detector simulations include the effect of the increased number of additional inelastic pp collisions (“pile up”) accompanying each beam crossing in the LHC. In CMS, simpler extrapolations are made, based on current physics analyses, and scaling signal and background by the change in cross sections and integrated luminosities from 8 to 14 TeV. Table 3 shows the projected mass reach for some representative processes.

Several studies have examined the prospects for detecting mass-degenerate Higgsinos in future LHC runs, based on the monojet signature [150,151,185,186]. Another interesting possibility is to use the process of vector boson fusion to search for near-degenerate electroweak partners; this is discussed in [187]. This is a rapidly evolving area of active investigation and conclusions from these studies vary in quantitative detail. Qualitatively, however, all studies indicate that probing near-degenerate Higgsinos at the LHC will remain challenging into the future.

Table 3: Projections from CMS and ATLAS for the 5σ discovery reach for selected processes at the 14 TeV LHC, assuming an integrated luminosity of 300 fb^{-1} .

Mode	Discovery reach		[Ref.]
	300 fb^{-1}	Comment	
simplified gluino-squark model	2700	$m_{LSP} \approx 0$	[182]
$\tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0\ t\bar{t}\tilde{\chi}_1^0$	1900	$m_{LSP} < \approx 900\text{ GeV}$	[183]
$\tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0\ b\bar{b}\tilde{\chi}_1^0$	1900	$m_{LSP} \approx 0$	[183]
$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0\ t\tilde{\chi}_1^0$	1000	$m_{LSP} < \approx 200\text{ GeV}$	[184]
$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0\ b\tilde{\chi}_1^0$	1050	$m_{LSP} \approx 0$	[184]
$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0\ Z\tilde{\chi}_1^0$	500-600	$m_{LSP} < \approx 100\text{ GeV}$	[183]
$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0\ h\tilde{\chi}_1^0$	400-500	$m_{LSP} \approx 0\text{ GeV}$	[183]
long-lived $\tilde{\tau}_1$	800	direct production	[183]
$TT \rightarrow bW/tZ/th(50\% : 25\% : 25\%)$	1000	vector-like quarks	[183]

5.2 Conclusions

The most naive expectations from naturalness have been dashed by the results from the Run I searches at the LHC, which so far find no BSM physics. In this article, we have summarized the current status of searches from ATLAS and CMS, with a focus on searches motivated by solutions to the hierarchy problem and searches for dark matter. A summary of these searches is shown in Tables 1 and 2.

The stringent limits on the existence of new physics at the LHC has led some to question the utility of naturalness as a guiding principle to BSM physics. At one extreme is the camp that is ready to abandon naturalness altogether; this camp is aided by the observation of what is consistent with a non-zero, but small, cosmological constant¹⁴ which implies a fine-tuning of 120 orders of magnitude [189] that is currently not understood. A less extreme view holds that some level of fine-tuning seems to be implied by the LHC results, but that naturalness is still useful to define the next energy scale milestones; in this view there is still much room to cover before we are faced with the full fine-tuning of 32 orders of magnitude that would be implied if no BSM physics appears before the Planck scale.

In our view it is still too early to worry that naturalness is in trouble. As described above, there remain broad categories of topologies without appreciable fine-tuning that have evaded searches so far. Furthermore, it is useful to be reminded that naturalness itself is not well-defined. In addition to the obviously subjective choice of the level of fine-tuning

¹⁴See for example [188] for a recent review.

that one calls unnatural, there are difficulties quantifying fine-tuning in the first place. A recent review of the issues can be found in Ref. [35]. At its core, the naturalness principle was only ever meant to be a rule of thumb, and as applied to the EW hierarchy, merely a rough expectation that there should be new physics somewhere around TeV scale. As we have seen, there are many well-motivated models where particles below a TeV are still allowed by the LHC. Indeed, in one extreme example, the LHC cannot even improve on LEP bounds for a Higgsino LSP, whose mass plays a key role in natural SUSY. Given these considerations, the story of searches for new physics at the energy frontier, still motivated by the hierarchy problem and by the existence of dark matter, remains compelling going into the future running of the LHC.

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